Muon –Electron Conversion (μ2e) at FNAL

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FNAL
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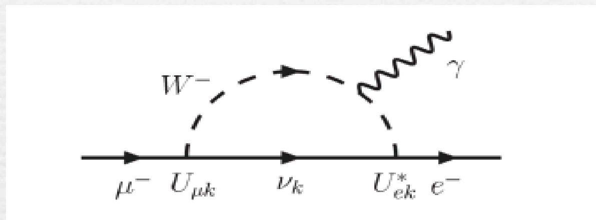
Motivation

- ν's have mass! Therefore individual lepton numbers are not good quantum numbers
- Therefore occurs in Charged Leptons as well



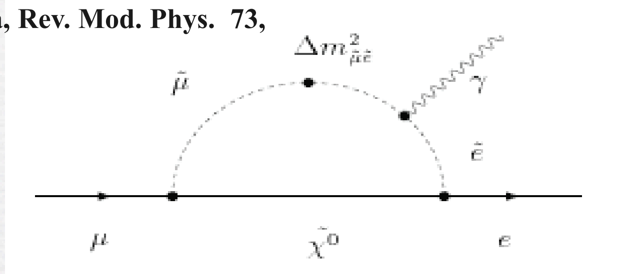
- Except neutrinos have to change flavor in loop...

$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$ ☹

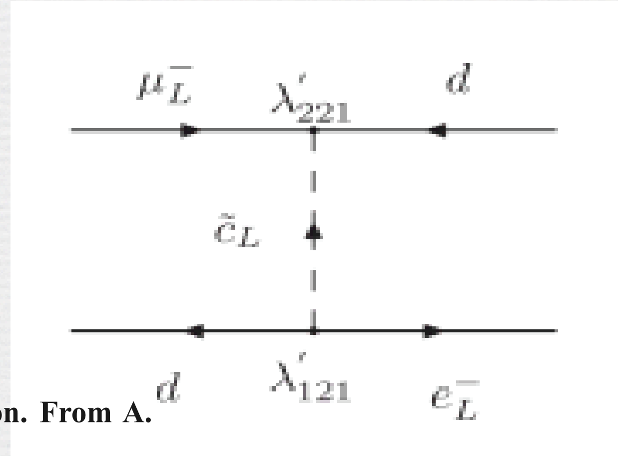
- But this is good! New physics not hidden by boring old neutrino oscillations

What New Physics?

MSSM slepton--neutralino contribution to $\mu \to e\gamma$. $\Delta m^2_{\mu e}$ stands for the insertion of an off-diagonal element of the slepton mass-matrix. From Y. Kuno and Y. Okada, Rev. Mod. Phys. 73, 151 (2001).



- Supersymmetry, for example: far better than $\mu \to e\gamma$
- Far Higher than LHC, > 1000 TeV



MSSM tree-level R-parity violating contribution to $\mu \to e$ conversion. From A. de Gouvea, S. Lola and K. Tobe, Phys. Rev. D63, 035004 (2001).

Major Contributions

Standard Model SuperSymmetry

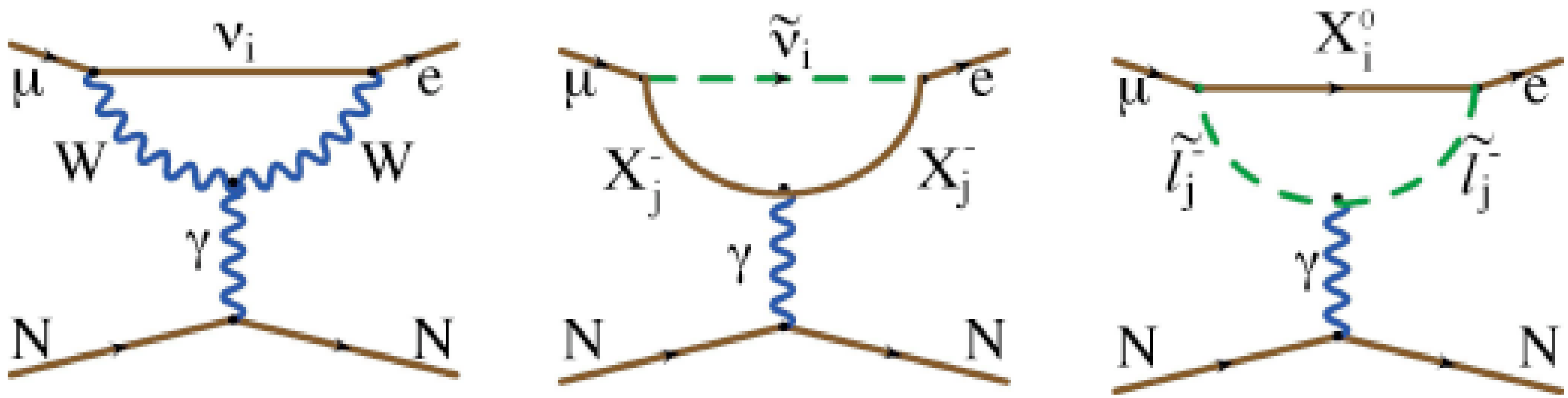
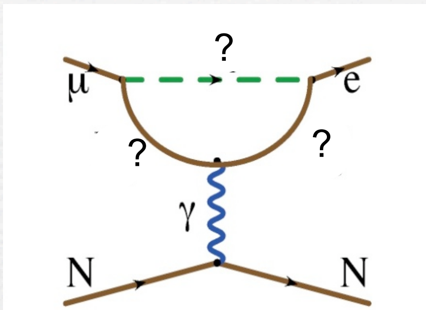


Figure 1.1: The leading Standard Model diagram for μ+N $\rightarrow$ e+N is shown on the left. The center and right figures are the dominant SUSY diagrams.

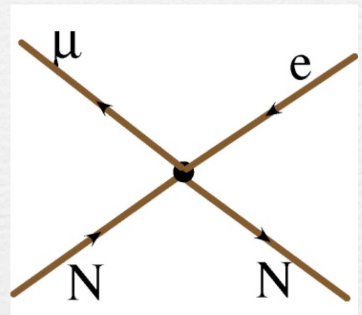
μe Conversion and $\mu \rightarrow e\gamma$

- ***Dipole/Penguin***



- This type of diagram gives rise to small CLFV through virtual neutrino mixing
- Also contributes to $\mu \rightarrow e\gamma$ if photon real

- ***Fermi Interaction***



- Corresponds to exchange of a new, massive flavor-changing neutral current particle
- ***Does not produce $\mu \rightarrow e\gamma$***

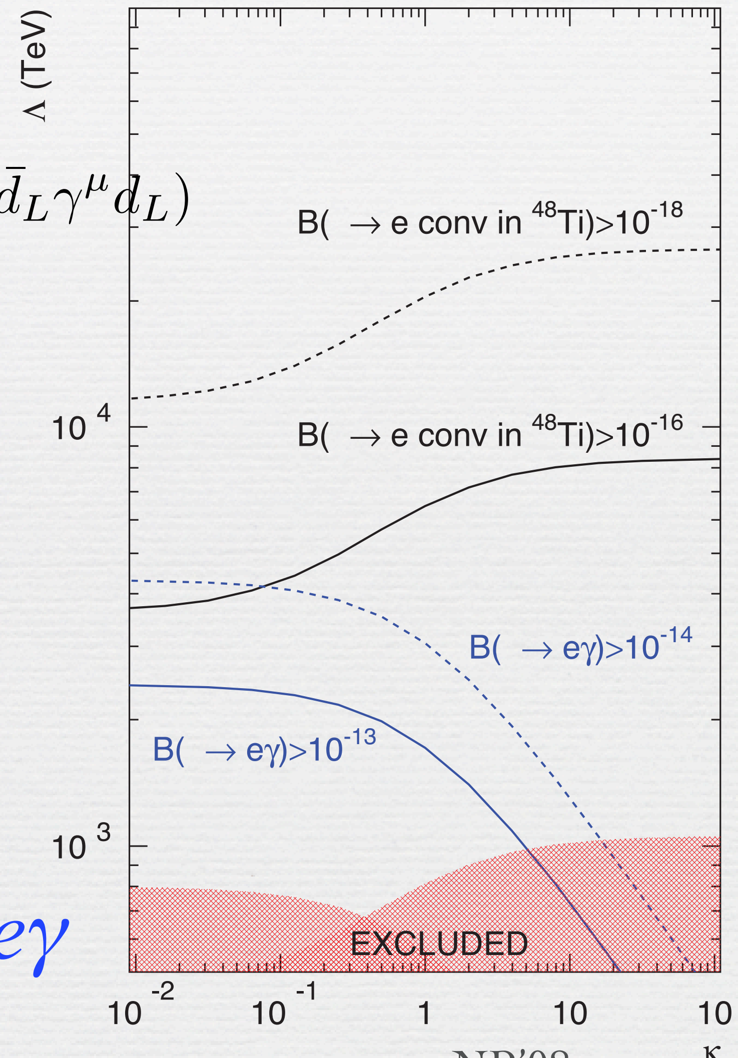
Overview of Reach

André de Gouvêa, Project X Workshop Golden Book

$$
\begin{aligned}
L_{\mathrm{CLFV}} &= \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} \\
&+ \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)
\end{aligned}
$$

Λ four-point, κ penguin

$$\frac{1}{\Lambda^2} = \frac{f^2}{16\pi^2}\frac{1}{M_{\mathrm{new}}^2} \qquad \kappa >> 1, \frac{1}{\Lambda^2} \sim \frac{g^2\theta_{e\mu}}{M_{\mathrm{new}}^2}$$



higher mass scale

Two Points:

1) Mass Reach of 10^4 TeV

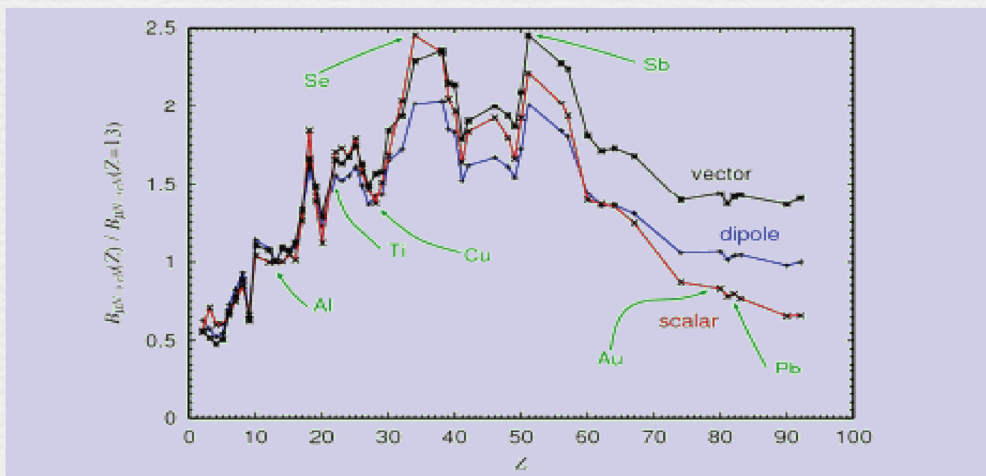
2) More Powerful than $\mu \rightarrow e\gamma$

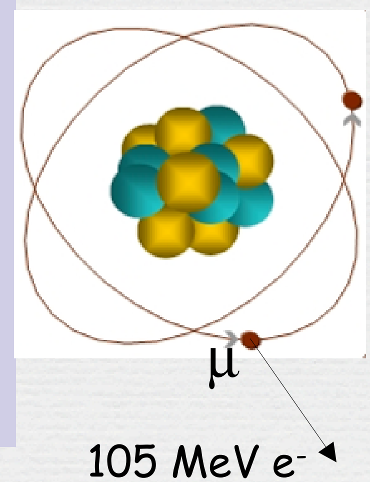
What Do We Measure?

- μ to e conversion in the field of a nucleus

$$R_{\mu e} \equiv \frac{\Gamma(\mu^- + (A,Z) \to e^- + (A,Z))}{\Gamma(\mu^- + (A,Z) \to \nu_\mu + (A,Z-1))}$$

- *Stop muons in target*
- Physics sensitive to Z: with signal, can switch target to probe source of new physics

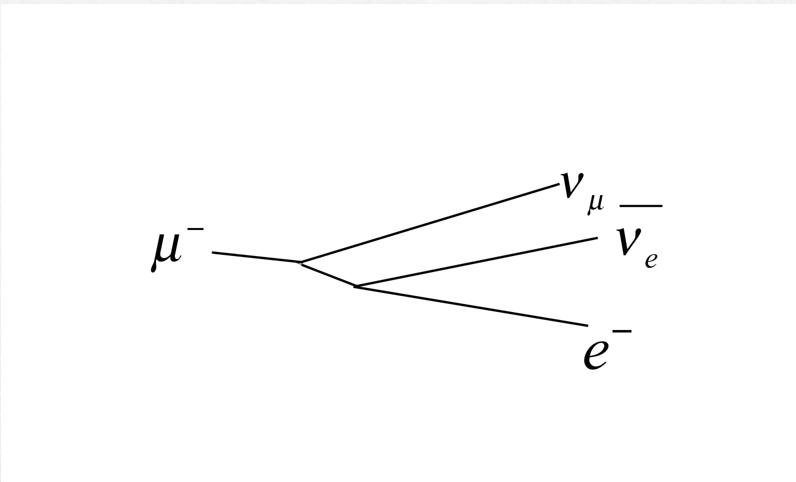


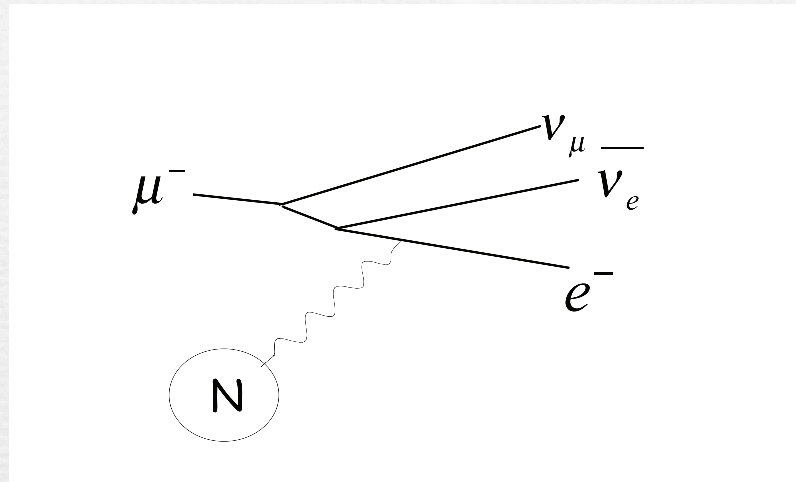


Backgrounds

- Decay-in-Orbit and Misreconstructions
  - resolution and redundancy
- Prompt, Beam Related
  - extinction, delayed live window
- Cosmic Rays
  - shielding

Decay-in-Orbit Background





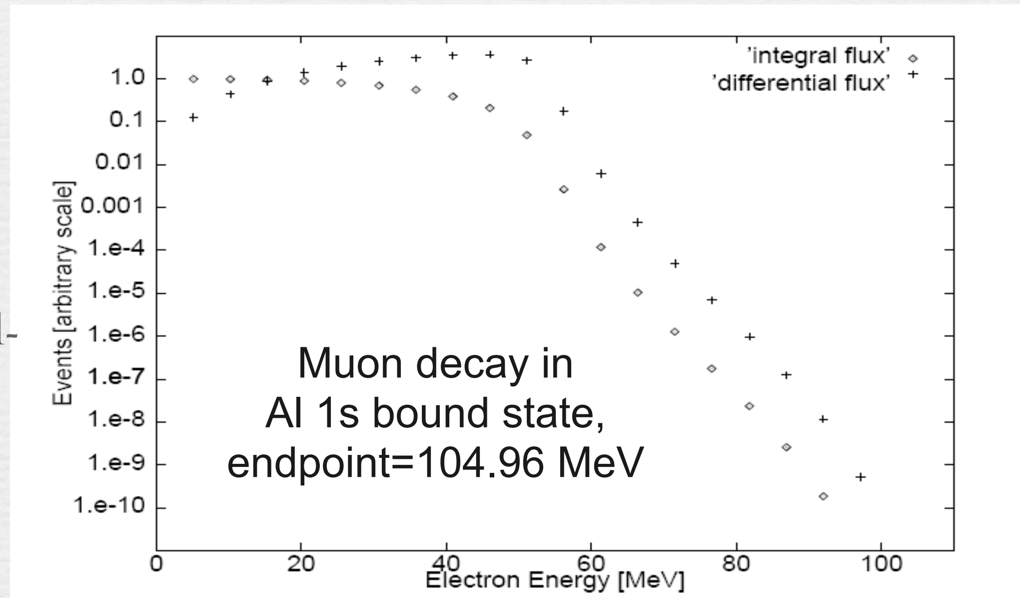
- High Rate
- Peak 52 MeV
- Detector *insensitive* to these

- Coherent balance of momentum
- Rate falls as $(E_{max} - E)^5$
- Drives Resolution

Decay-In-Orbit Details

- $E_e(max) = (m_\mu c^2$ - NuclearRecoilEnergy -AtomicBindingEnergy)
- For Z=13 (Al), Atomic BE=0.529 MeV, Recoil energy=0.208 MeV $\rightarrow$ Ee(max) =104.96 MeV
- Rate near the maximum energy falls very rapidly. Near endpoint: proportional to $(E_e(max)-E)^5$
- Major potential source of background- Discriminate against it with good electron energy resolution, ~1 MeV FWHM for μ2e

looks exactly like signal except for electron energy

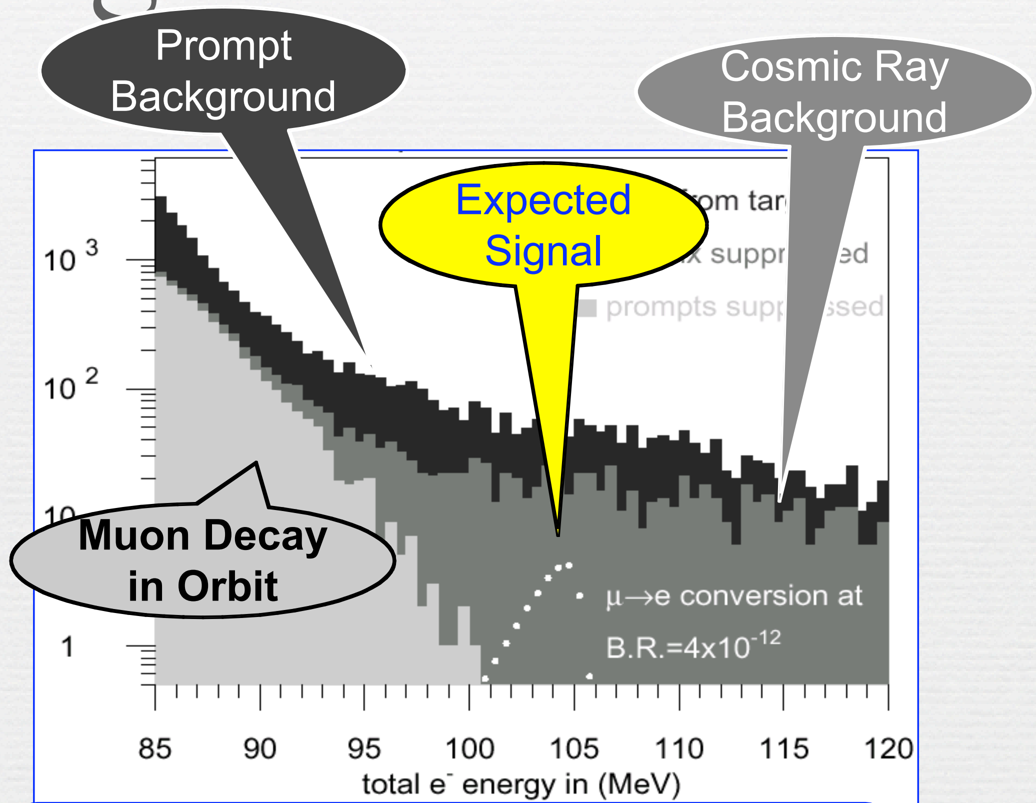


Prompt Backgrounds

- Prompt: due to beam particles which interact almost immediately when they enter the detector region,
  - Radiative pion capture, $\pi^- + A(N,Z) \to \gamma + X$.
    - $\gamma \to e^+e^-$; if one electron ~ 100 MeV in the target, looks like signal. Major limitation in SINDRUM II.
  - Beam electrons: incident on the target and scatter into the detector region. Need to suppress e^- with E>100 MeV near endpoint
  - In-flight muon decays

Existing Limits

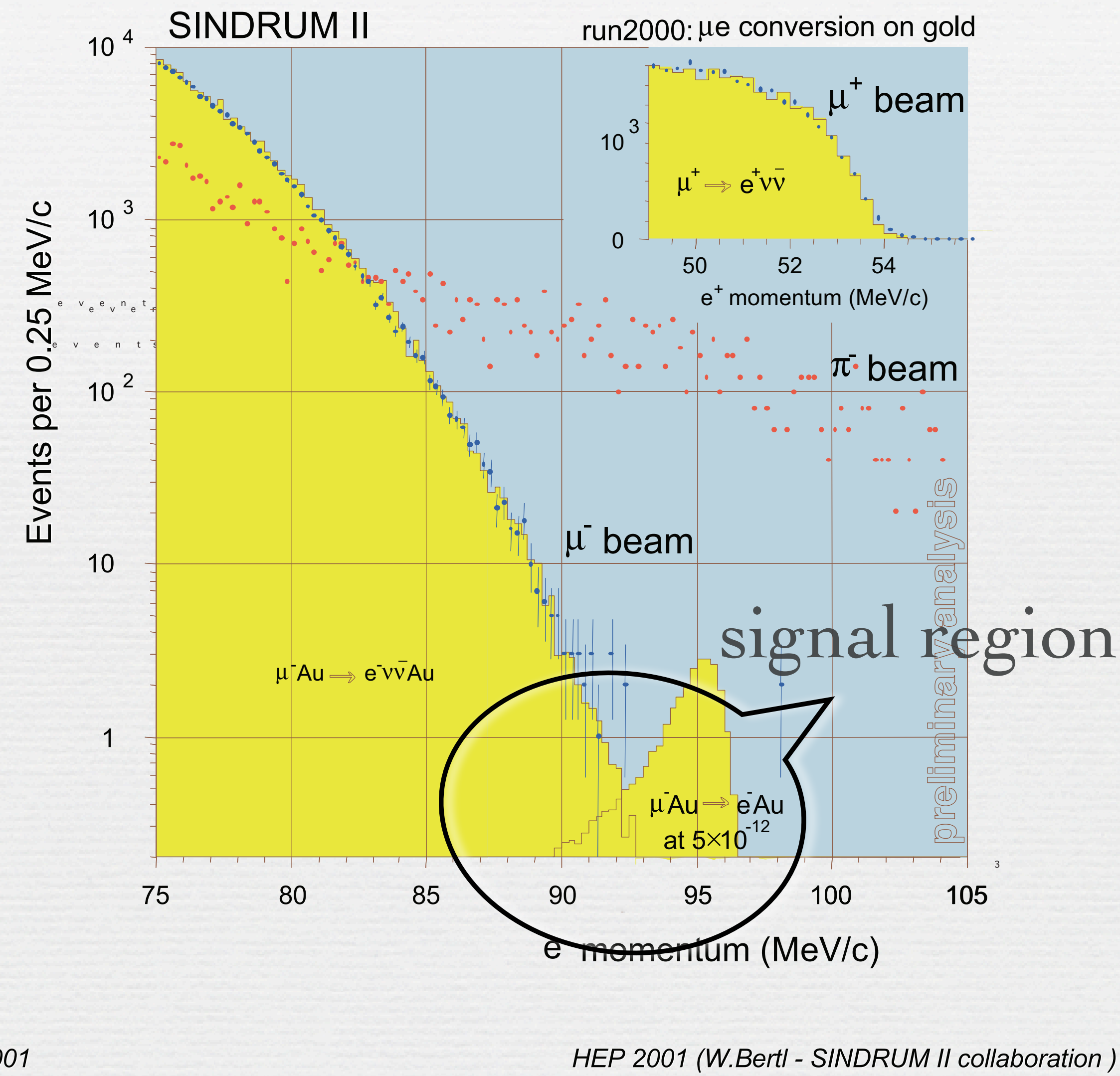
- $R_{\mu e} < 6.1 \times 10^{-13}$ in Ti (SINDRUM)
- Want to probe to 10^{-16} or better
- Factor of 10^4 improvement non-trivial



Experimental signature is 105 MeV e^- originating in a thin Ti stopping target

Scary Plot

- Final SINDRUM -II on Au
- Note Background in Signal Region
- Multiply by 10^4

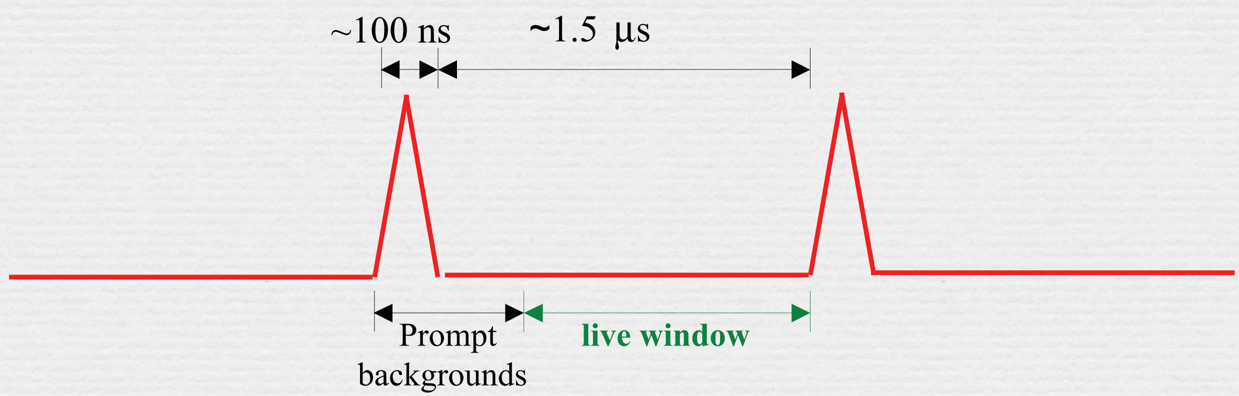


μ2e at FNAL

- Improvements:
  - $>10^3$ increase in muon intensity from SINDRUM
    - High Z target for improved pion production
    - Graded solenoidal field to maximize pion capture
  - Pulsed beam to eliminate prompt backgrounds
    - must achieve required extinction *and measure it*
- Resolution for Decay-In-Orbit Critical

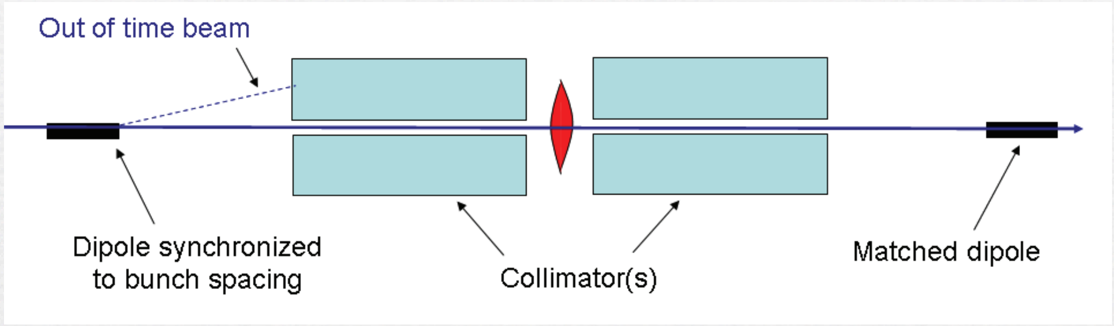
Pulsed Beam

- Beam pulse duration << τ_μ, Pulse separation $\approx \tau_\mu$
- Large duty cycle
- Extinction between pulses < 10^{-9} (assume this for calculations)



Measuring Extinction Rate

- Protons in beam between pulses:



- "Switch" dipole timing to eliminate bunches, accept background for direct measurement
- Other schemes under investigation
  - Measurement: collimators and telescope?

Outline of Remainder

- Beam pre- and post-Project X:
  - how do we get muons to target? how many? time structure?
- Detector:
  - How Do We Achieve Required Rejection and Resolution?

8 GeV Power

20 kW (current)

200 kW (Project X)

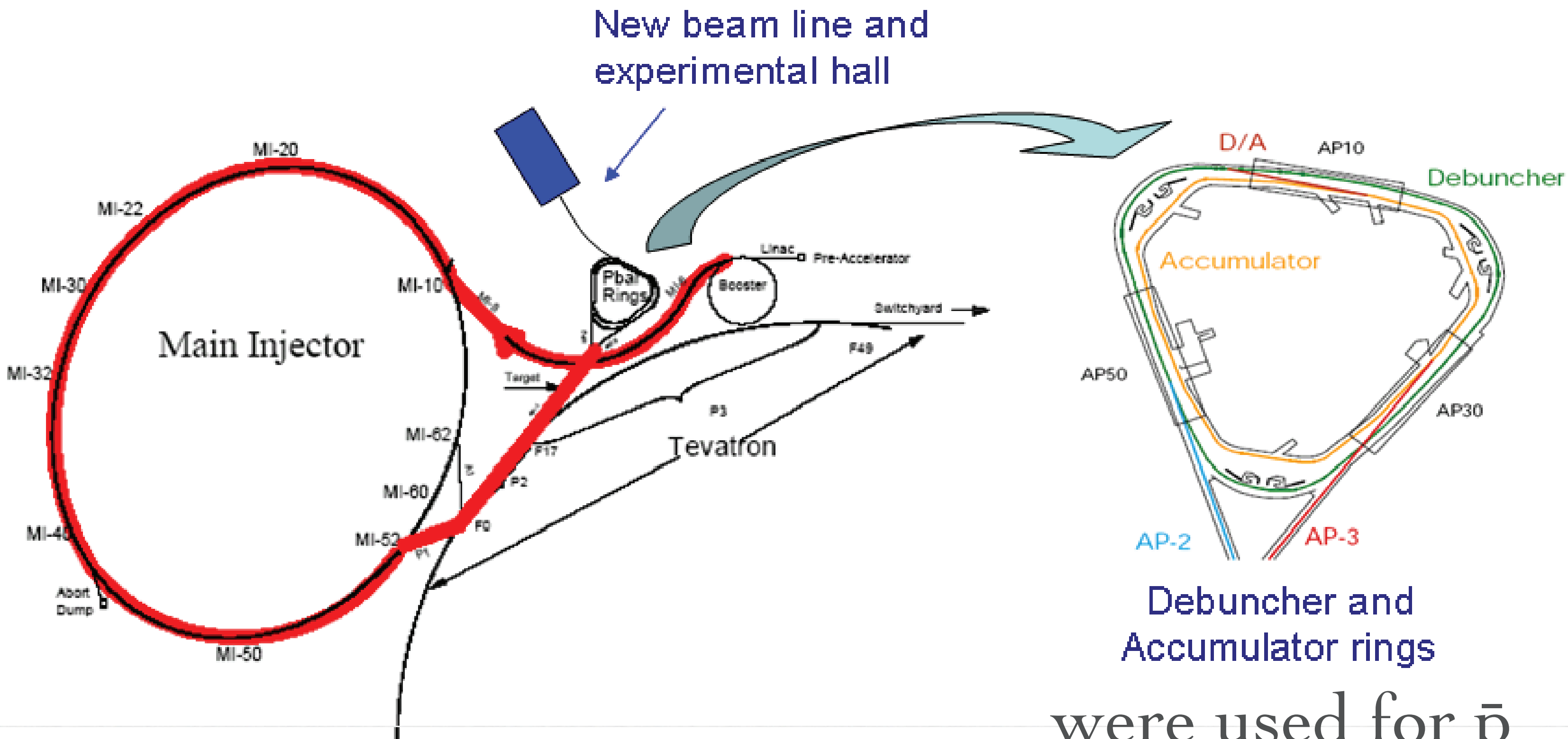
2000 kW (Project X Upgrades)

Intensity Summary

	MECO	Mu2e Booster	Mu2e Project X, no expt. upgrade	Mu2e Project X, expt. upgrade
protons/sec	40×10^{12} (design)	18×10^{12}	70×10^{12}	160×10^{12}
average beam power	50 kW (design)	23 kW	90 kW	200 kW
duty factor	0.5 s on, 0.5 s off, 50%	90%	90%	90%
instantaneous rate	80×10^{12} (design)	20×10^{12}	77×10^{12}	220×10^{12}
short term beam power	100 kW (design)	25 kW	100 kW	220 kW
Beam pulse period, msec	1.35	1.65	1.65	1.65
Data collection time interval msec	0.7-1.35	0.7-1.65	0.7-1.65	0.7-1.65

Booster-Era Beam

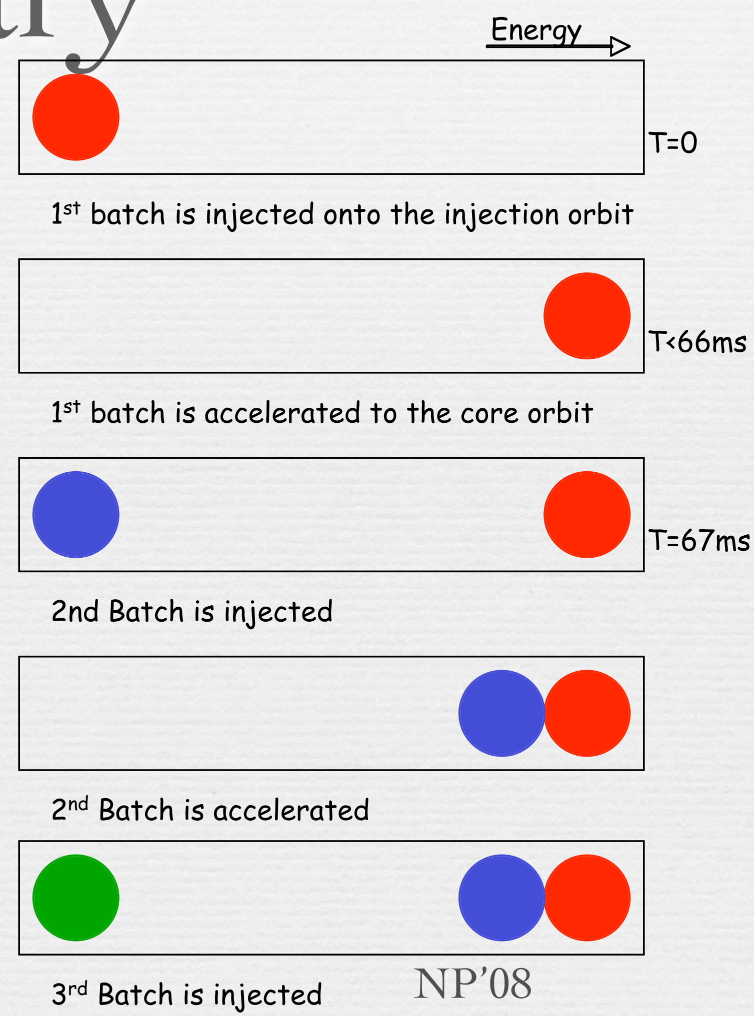
- After TeVatron shut-down, Accumulator, Debuncher, and Recycler “freed” from antiprotons



were used for $\bar{p}$

Quick Fermilab Glossary

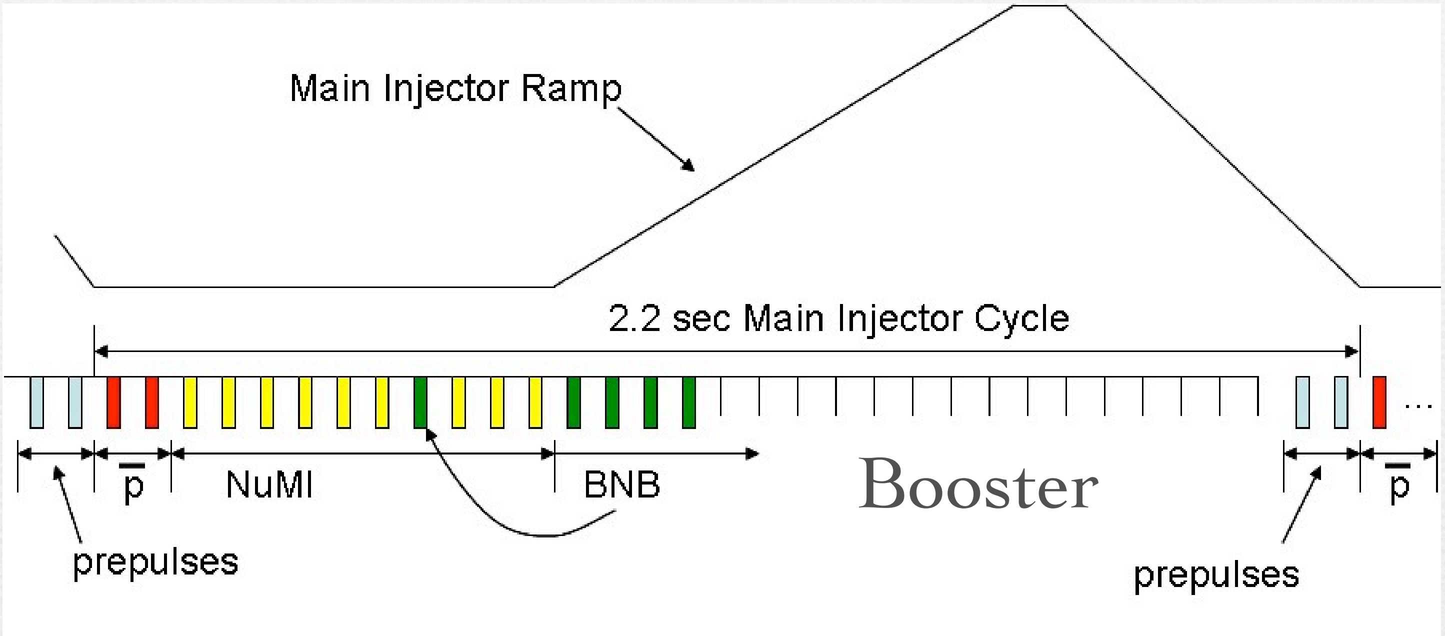
- Booster:
  - The Booster accelerates protons from the 400 MeV Linac to 8 GeV
- Accumulator:
  - momentum stacking successive pulses of antiprotons now, 8 GeV protons later
- Debuncher:
  - smooths out bunch structure to stack more $\bar{p}$
- Recycler:
  - holds more $\bar{p}$ than Accumulator can manage, “store” here



Overall Scheme

- Now:
  - Booster-MI-Recycler
  - MI is limiting since must load MI fully before accelerating to 120 GeV
- In NovA/μ2e era:
  - Booster-Recycler and slip-stacking
  - Load into Recycler while accelerating in MI
- In Project X Era:
  - Linac-Recycler

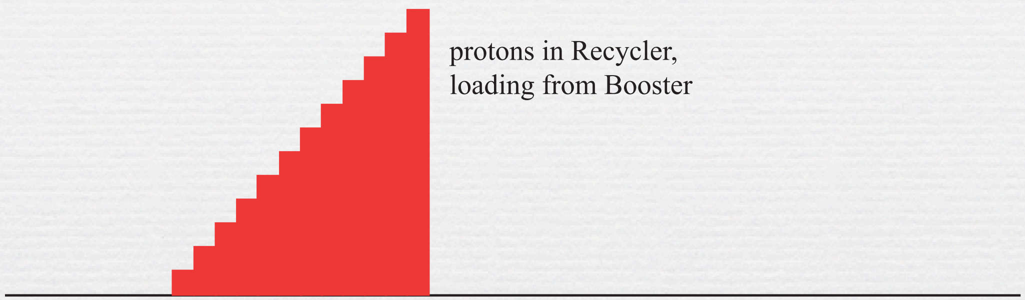
Details, details...



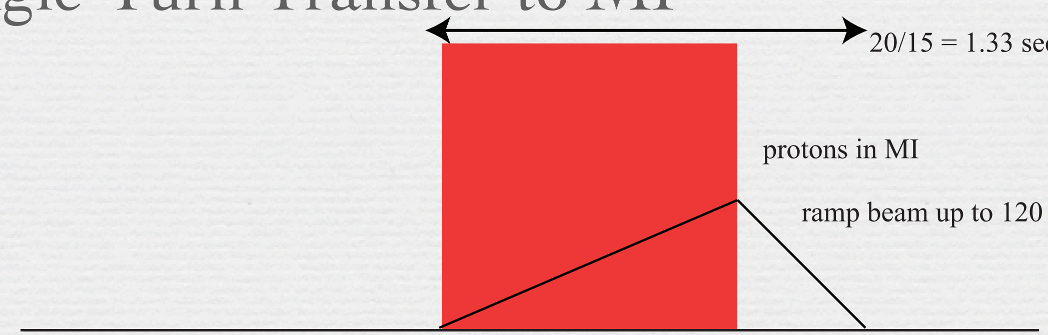
- In order to increase protons to the NOvA neutrino experiment after the collider program ends, protons will be "stacked" in the Recycler while the Main Injector is ramping, thereby eliminating loading time.

NovA Era

- Load from Booster to Recycler

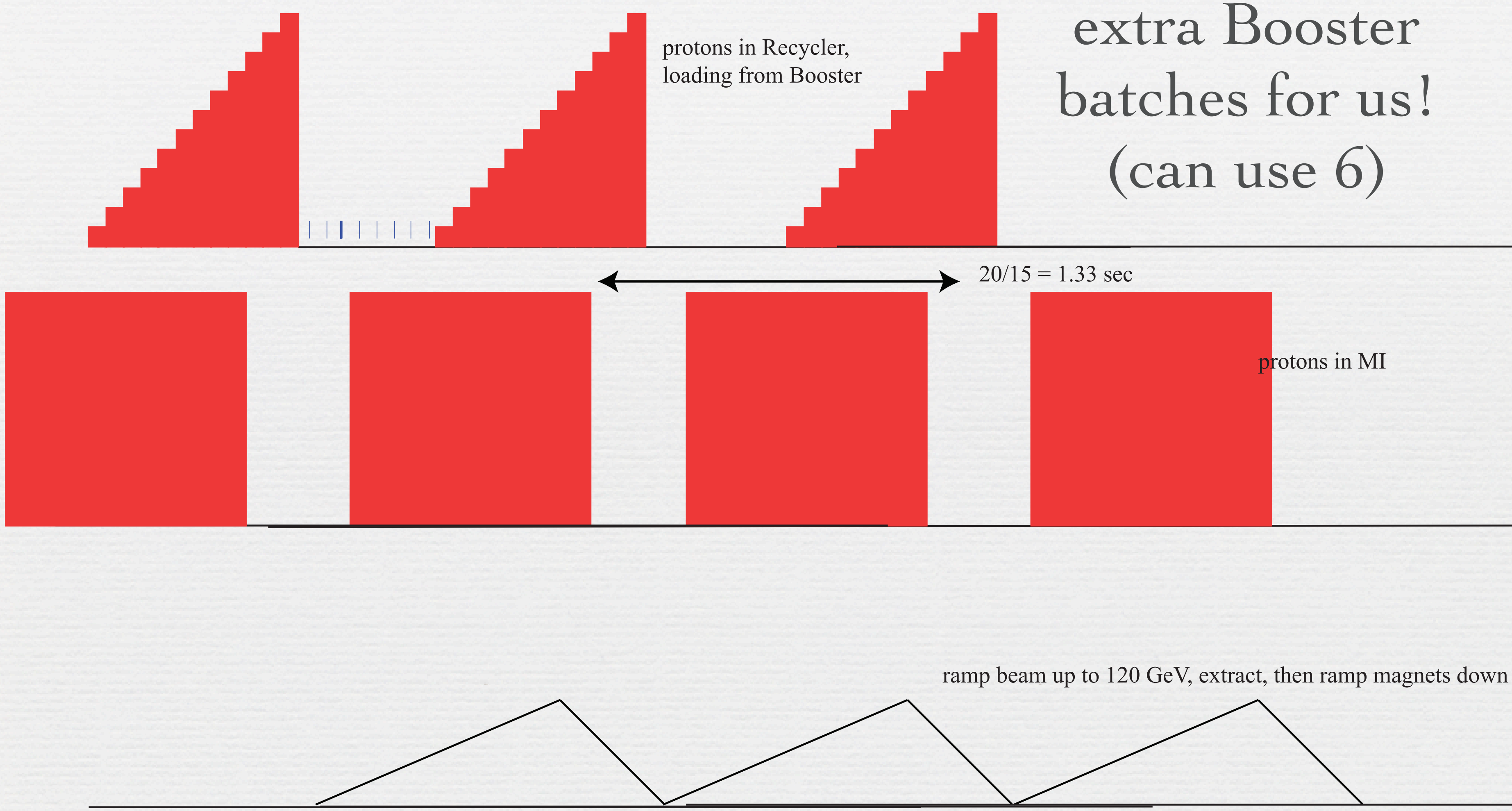


- Single-Turn Transfer to MI



All Together...

can fit eight extra Booster batches for us! (can use 6)



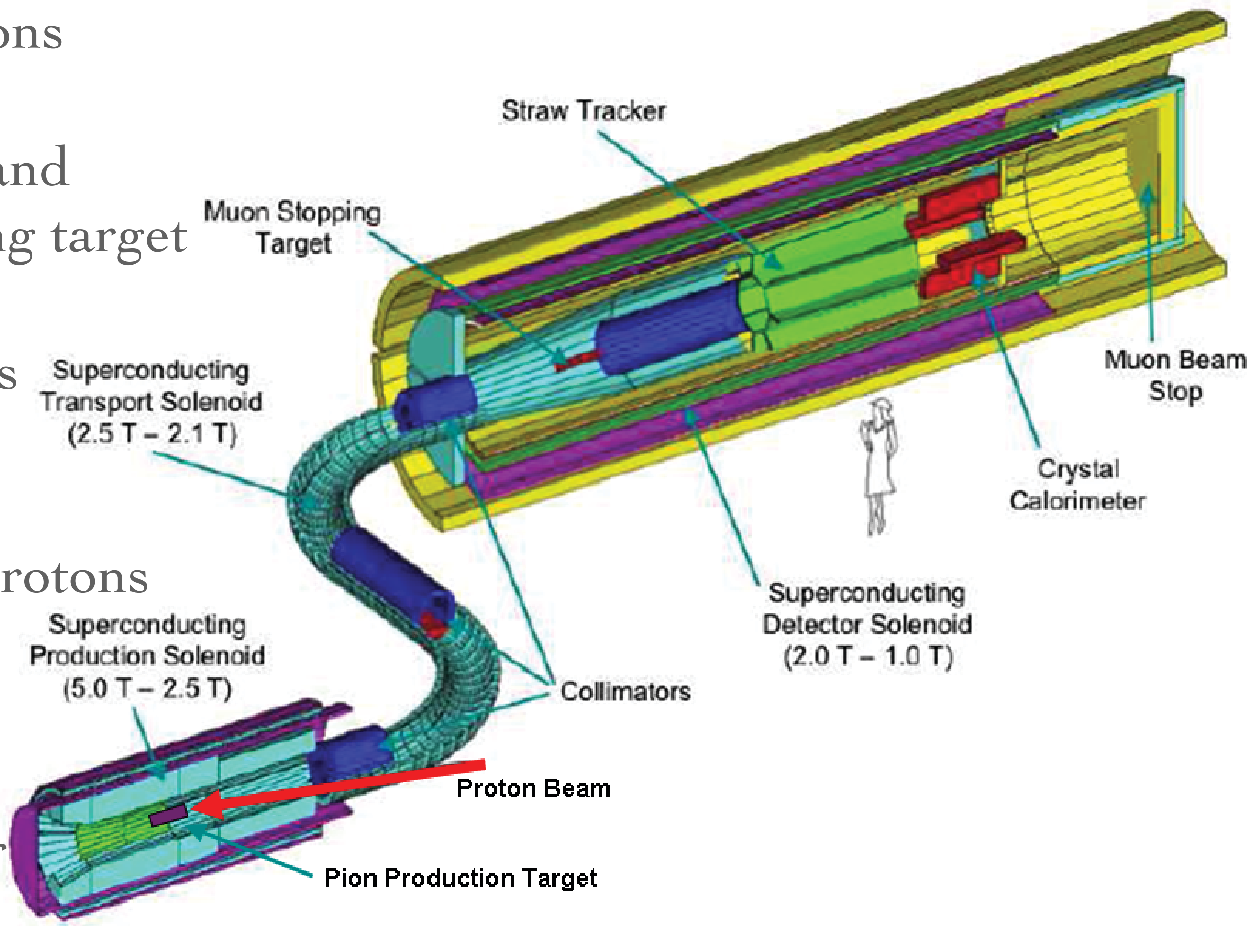
Project X Upgrades

- Ultimate sensitivity would be provided by Project X linac as proton source
  - Deliver up to 200 kW average beam current:
    - ~3 x 10^{14} protons/sec at 8 GeV (x10 previous slide)
    - 9mA, 1 msec, 5 Hz
- Three Upgrades for x10 from 200 kW to 2000 kW at 8 GeV:
  - Increase Pulse Length
  - Increase Repetition Rate
  - Increase Number of Klystrons

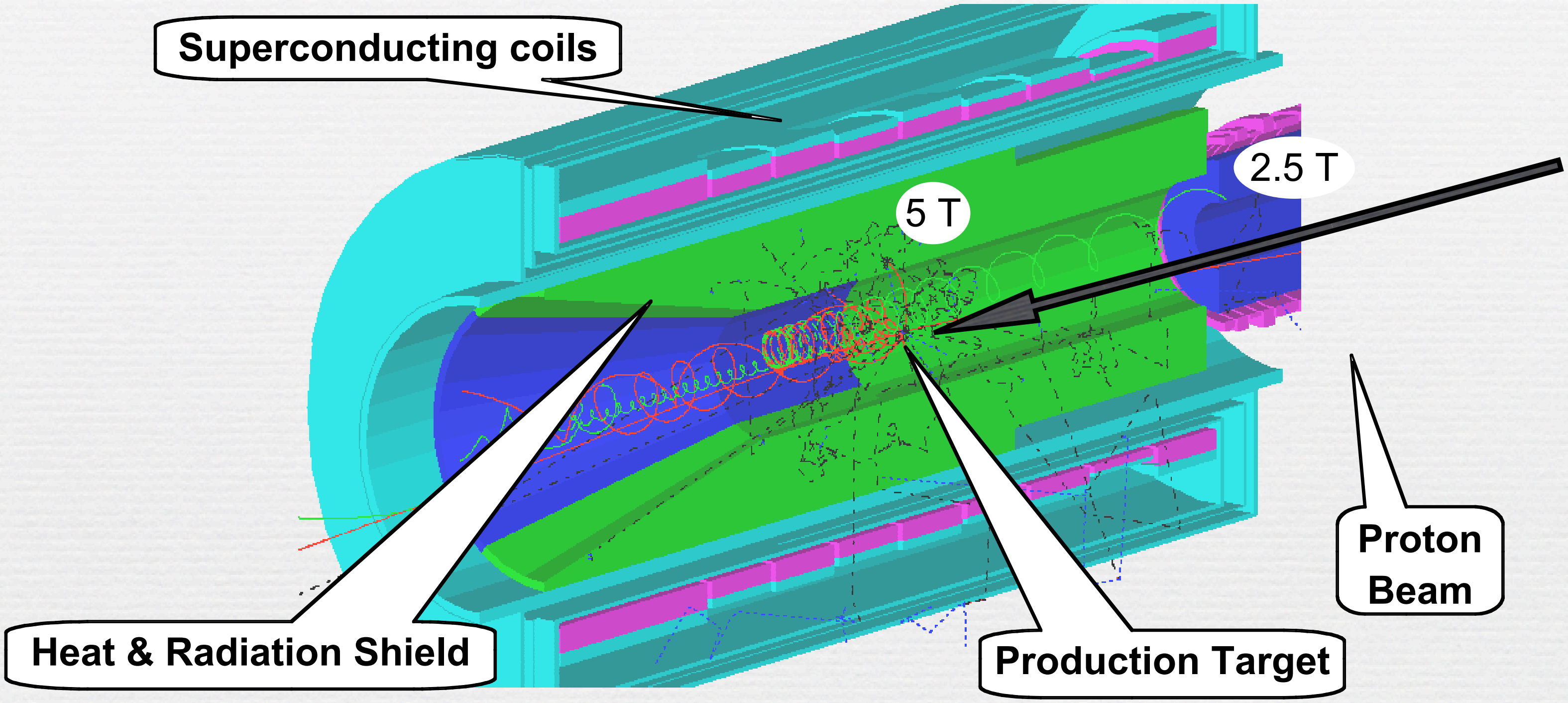
don't know how to use this yet, but we're happy to think about it!

Overview of Experiment

- Magnetic bottle trapping backward-going pions
- Decay into muons and transport to stopping target
- “S”-curve eliminates backgrounds
- Absorbers for antiprotons
- Tracking
- Crystal Calorimeter



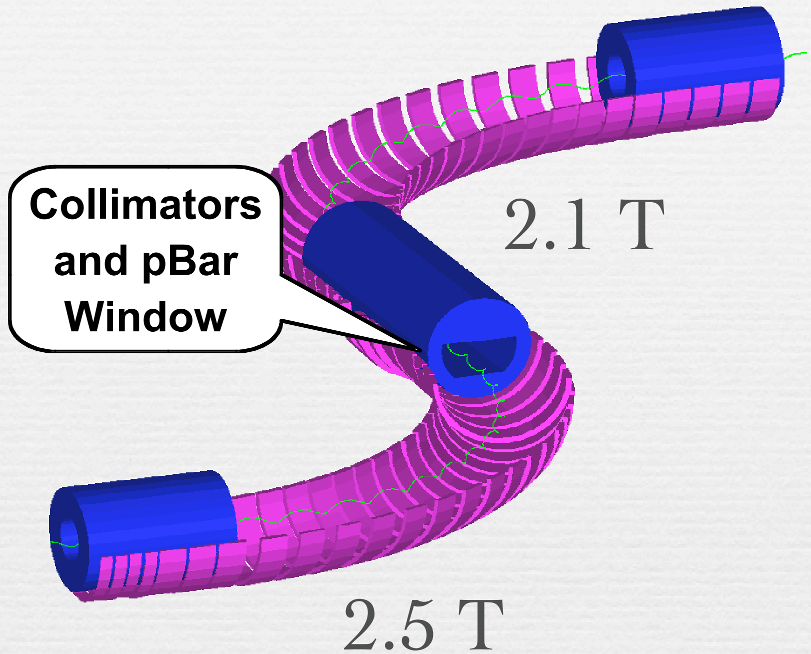
Production Region

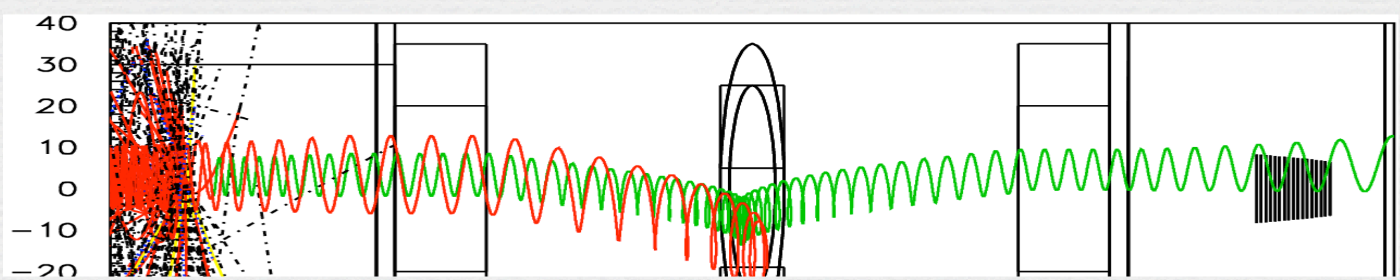


- **Axially graded 5 T solenoid captures low energy backward and reflected pions and muons, transporting them toward the stopping target**
- Cu and W heat and radiation shield protects superconducting coils from effects of 50kW primary proton beam: need upgrade from MECO design for > 50 kW

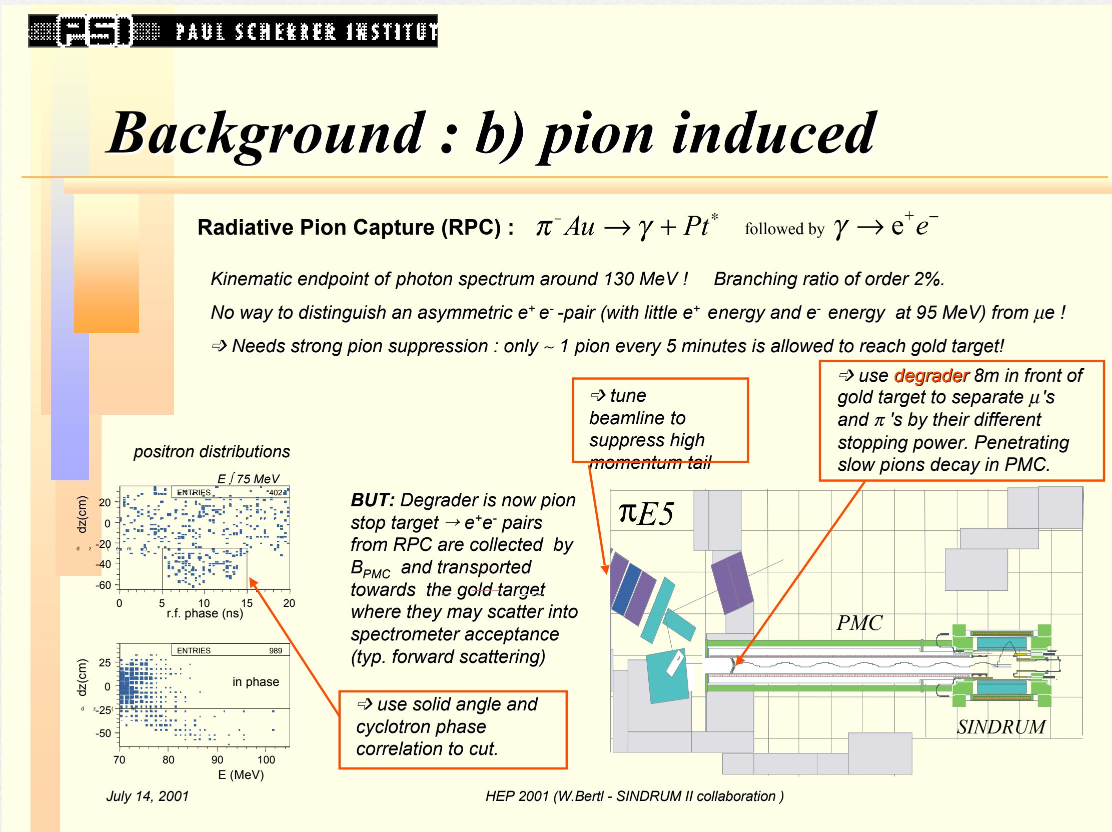
Transport Solenoid

- Curved solenoid eliminates line-of-sight transport of photons and neutrons
- Curvature drift and collimators sign and momentum select beam
- dB/ds < 0 in the straight sections to avoid trapping which would result in long transit time



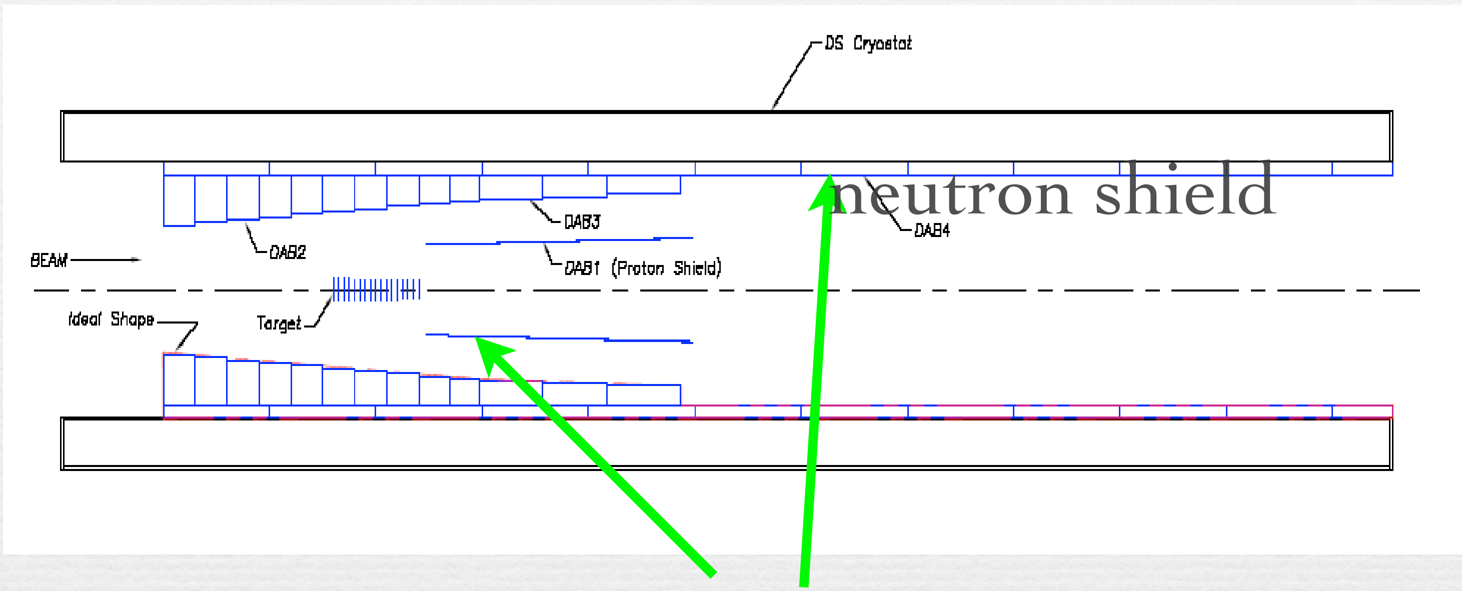


Key Improvement of Both COMET and $\mu 2e$



Curved Transport Solenoid in both modern expt's

Stopping Target Region



CH2 shields

- Conical Shield Reduces background and high rate from protons produced in stopping target
- Outer shield absorbs neutron cloud

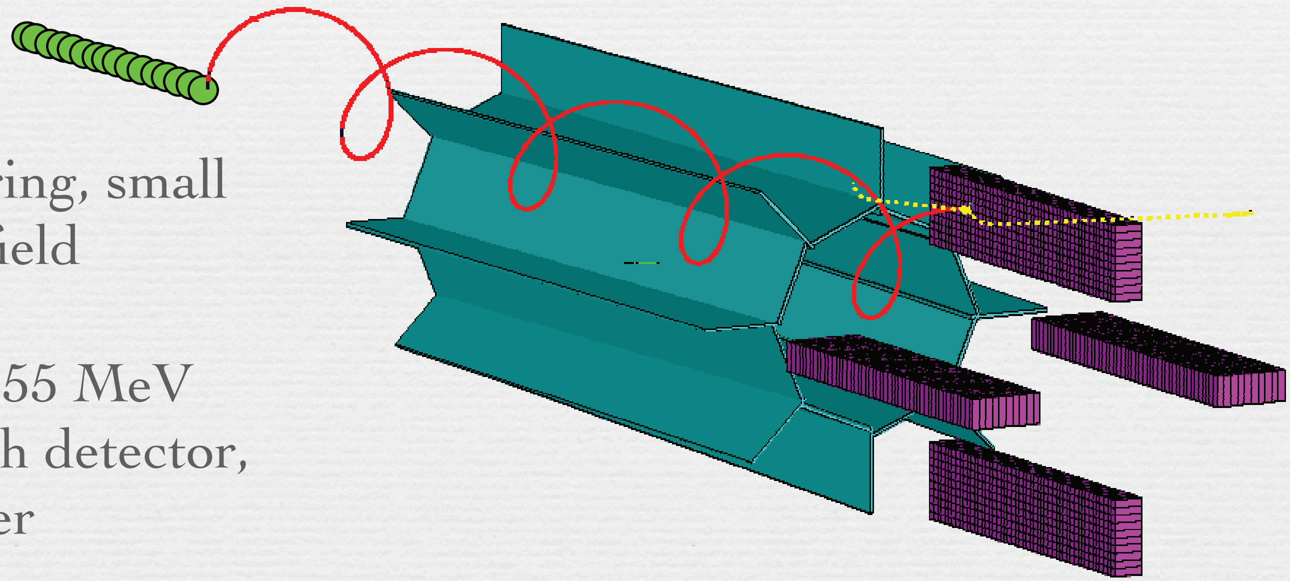
Detector

- Octagon and Vanes of Straw Tubes
- Immersed in solenoidal field, so particle follows near-helical path
  - dE/dx, scattering, small variations in field
- Particles with $p_T < 55$ MeV do not pass through detector, but down the center
- Followed by Calorimeter

σ= 200 μ transverse, 1.5 mm axially

2800 axial straw tubes, 2.6 m by 5 mm, 25μ thick

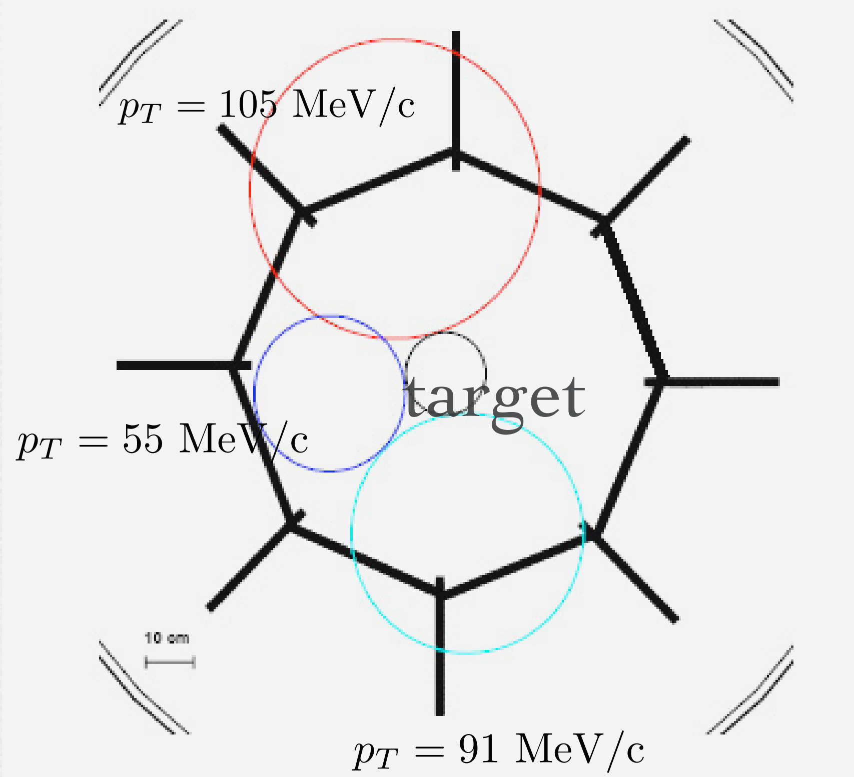
use return yoke as CR shield



σ /E = 5%, 1200 3.5 X 3.5 X 12 cm $PbWO_4$

Beam's Eye View

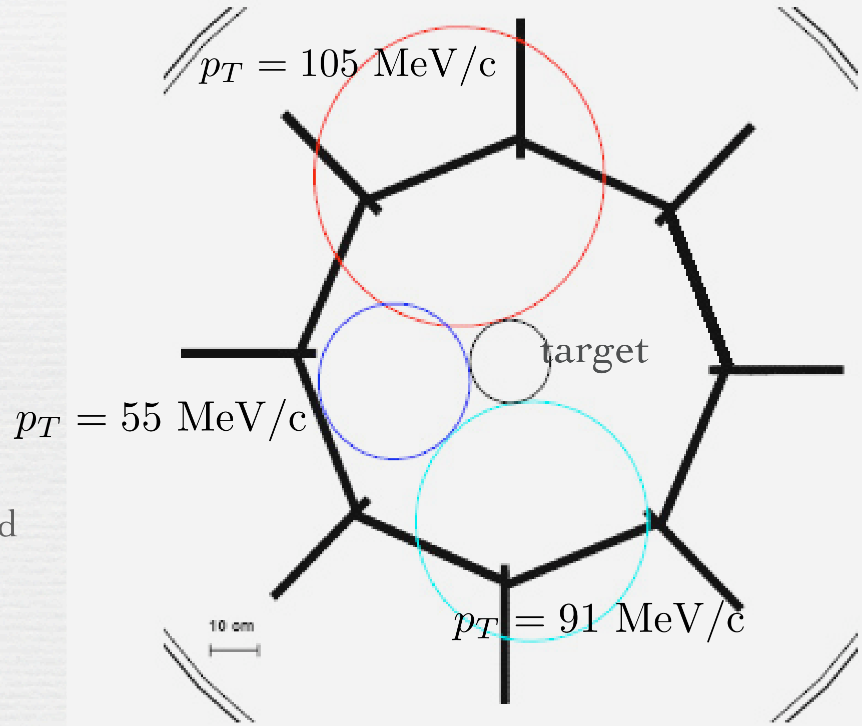
- Below $p_T = 55$ MeV, electron stays inside tracker and is not seen
- Looking for helix as particle propagates downstream
- More "vanes" fire as momentum increases



Note: <0.3% of e- from DIO have p_T>55 MeV/c

Details

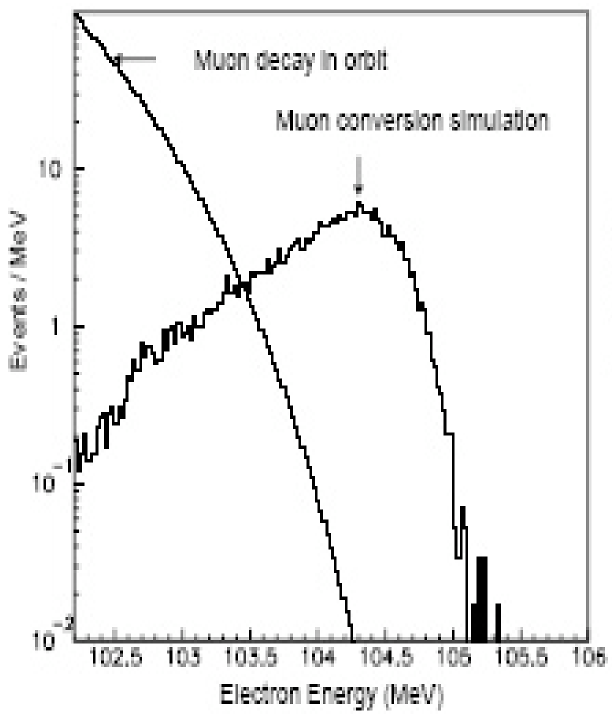
- 38 -70 cm active radius
- Geometry: Octagon with eight vanes, each ~30 cm wide x 2.6 m long
- Straws: 2.9 m length 5mm dia., 25 mm wall thickness to minimize multiple scattering – 2800 total
- Three layers per plane, outer two resistive, inner conducting
- Pads: 30 cm 5mm wide cathode strips affixed to outer straws - 16640 total pads
- Position Resolution: 0.2 mm (r,φ) X 1.5 mm (z) per hit is goal
- Energy loss and straggling in the target and multiple scattering in the chambers dominate energy resolution of 1 MeV FWHM



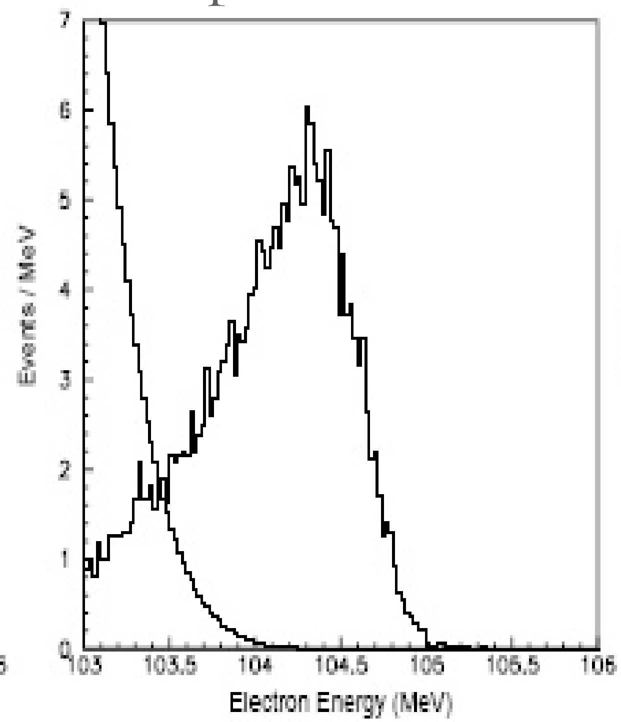
Decay-In-Orbit

- $R_{e\mu}=1\text{x}10^{-16}$, Energy resolution 1 MeV (FWHM)

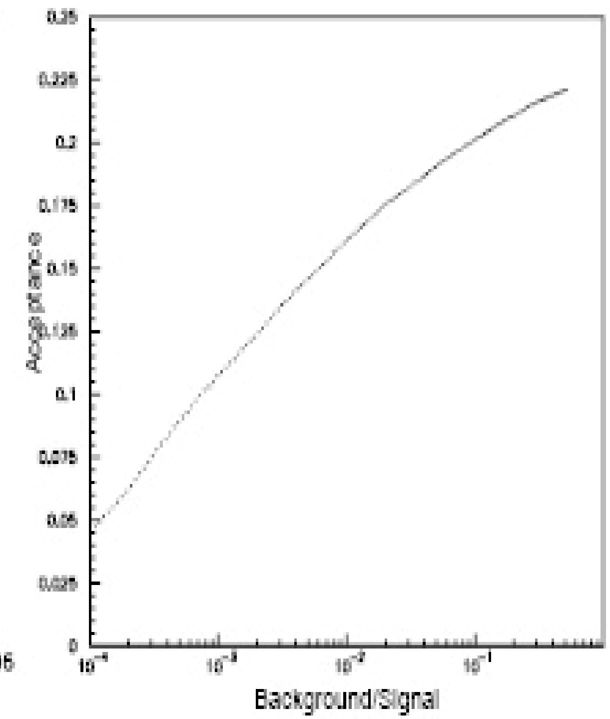
- Resolution is most important factor



Log scale



Linear scale



Acceptance and S/B as E_{thresh} varied

Other Backgrounds

- Delayed: due to beam particles which take > ~ few hundred nanoseconds before they produce signals in the detectors on average
  - Protons, neutrons, gammas from muon capture
  - Photons from radiative muon capture
- Antiproton annihilations along beam line or near target- (none in SINDRUM II, potential problem for μ2e)
- Cosmic Rays- Back/Signal proportional to (run time)/(beam intensity) (can measure off-spill)

Some of Backgrounds...

Type	Description
e_t	beam electrons
n_t	neutrons from muon capture in muon stopping target
γ_t	photons from muon capture in muon stopping target
p_t	protons from muon capture in muon stopping target
$e(DIO)_t < 55$	DIO from muon capture in muon stopping target, $<$ 55 MeV
$e(DIO)_t > 55$	DIO from muon capture in muon stopping target, $>$ 55 MeV
n_{bd}	neutrons from muon capture in beam stop
γ_{bd}	photons from muon capture in beam stop
$e(DIO)_{bd} < 55$	DIO from muon capture in beam stop, $<$ 55 MeV
$e(DIO)_{bd} > 55$	DIO from muon capture in beam stop, $>$ 55 MeV
$e(DIF)$	DIO between stopping target and beam stop

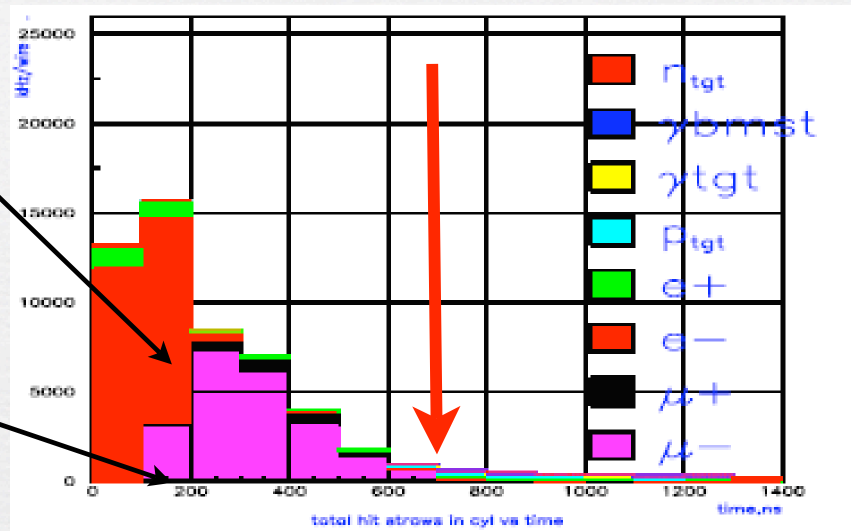
bd = albedo from beam stop

Backgrounds vs. Time

700 nsec

beam e⁻

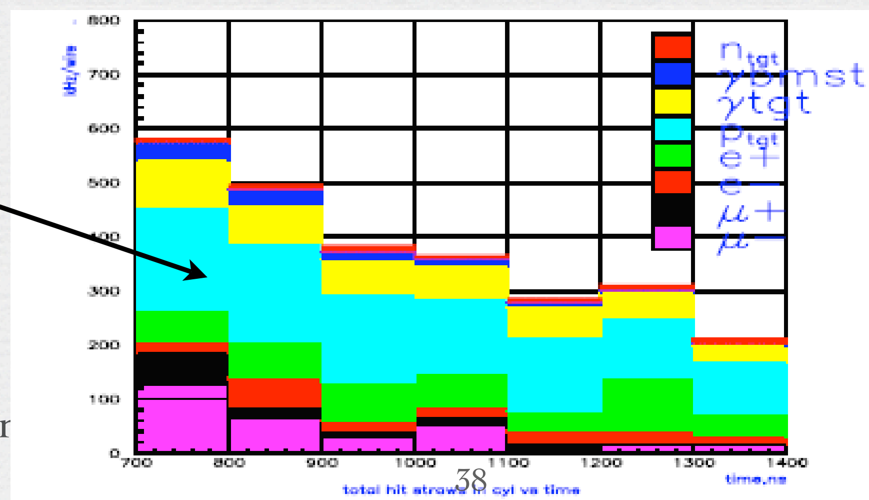
μ DIF



0-1400 nsec

Rate (MHz)

μ Capture Protons



700-1400 nsec

Rate (kHz)

Rates In Tracker

- Rates at *Beginning* of > 700 nsec Time Window, so these are highest
- Rates are manageable

Type	Rate(Hz)	$\mathcal{P}$ hit	Mean N hits/bkg part	$\mathrm{R_{wire}}$ (kHz)
e_t	2.7×10^{11}	0.00032	1.54	65
n_t	2.43×10^{11}	0.000142	2.887	49
γ_t	2.43×10^{11}	0.000248	4.524	134
p_t	0.181×10^{11}	0.00362	6.263	202
$e(DIO)_t < 55$	0.795×10^{11}	9.8×10^{-5}	1.44	5.5
$e(DIO)_t > 55$	2.07×10^{8}	0.00127	22.7	2.1
n_{bd}	0.475×10^{11}	7.1×10^{-5}	5.0	5.9
γ_{bd}	0.475×10^{11}	8.3×10^{-5}	4.5	6.1
$e(DIO)_{bd} < 55$	2.1×10^{11}	8.9×10^{-5}	1.	6.6
$e(DIO)_{bd} > 55$	5.46×10^{8}	1.82×10^{-4}	1.5	0.05
$e(DIF)$	2.74×10^{6}	1	35.84	34.5
total				464

Final Backgrounds

- For $R_{\mu e} = 10^{-16}$ expect 5 events to 0.5 bkg
- Extinction factor of 10^{-9}

5 signal

Source	Number/ 4 x 10^{20}
DIO	0.25
Radiative π capture	0.08
Scattered e^-	0.04
μ DIF	0.08
π DIF	<0.004

Measuring Background

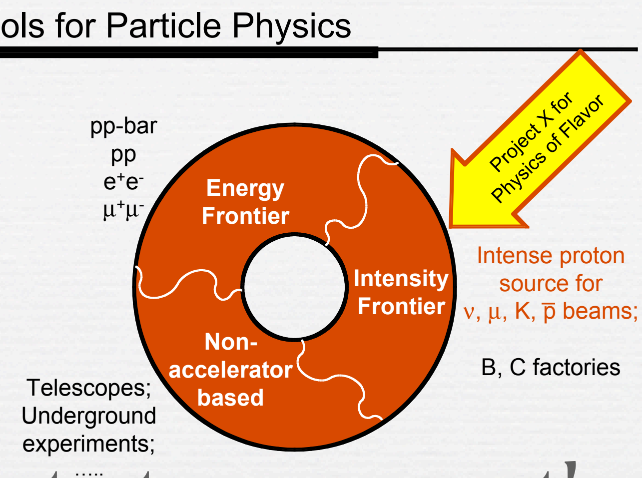
Source	Method
Energy Resolution	$\pi^+ \rightarrow e^+ \nu_e$ with reduced field
Misreconstructed Tracks	Relax calorimeter/ track agreement
False Tracks (from extra hits)	Allow missing hits, and measure "single hit" rate

Cost and Schedule

~$100M *~2014*

- A detailed cost estimate of the MECO experiment had been done just before it was cancelled:
  - Solenoids and cryogenics: **$58M**
  - Remainder of experimental apparatus: **$27M**
  - Additional Fermilab costs have not been worked out in detail, but are expected to be on the order of **$10M.**
- Hope to begin Accelerator work along with NOvA upgrade ~2010 (or 2011 if Run II extended)
  - Based on the original MECO proposal, we believe the experiment could be operational within five years from the start of significant funding
  - Driven by magnet construction.
- With the proposed beam delivery system, the experiment could collect the nominal $4x10^{20}$ protons on target in about one to two years, with no impact on NOvA

Conclusions



- **The μ2e experiment is an important measurement!**
- In the initial phase (without Project X) we would either:
  - *Reduce the limit for $R_{\mu e}$ by more than four orders of magnitude ($R_{\mu e} < 6 \times 10^{-17}$ @ 90% C.L.)*
  - *Discover unambiguous proof of Beyond Standard Model physics*
- **With a combination of Project X and/or improved muon transport, we could either**
  - Extend the limit by up to two orders of magnitude
  - Study the details of new physics